Appendix I. Overview of Stream Heating Processes

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Appendix I. Overview of Stream Heating Processes

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At any particular time, a defined stream reach is capable of sustaining a particular water column temperature. Stream temperature changes that result within a defined reach are explained rather simply. The temperature of a parcel of water traversing a stream/river reach enters the reach at a given temperature. If that temperature is greater than the energy balance of the stream reach is capable of supporting, the temperature will decrease. If that temperature is less than energy balance is capable of supporting, the temperature will increase. Stream temperature changes within a defined reach are induced by the difference in energy balance between the parcel of water and the surrounding environment and transport of the parcel through the reach. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer), and stream temperature changes are outlined in the flow chart below (Figure I-1.).

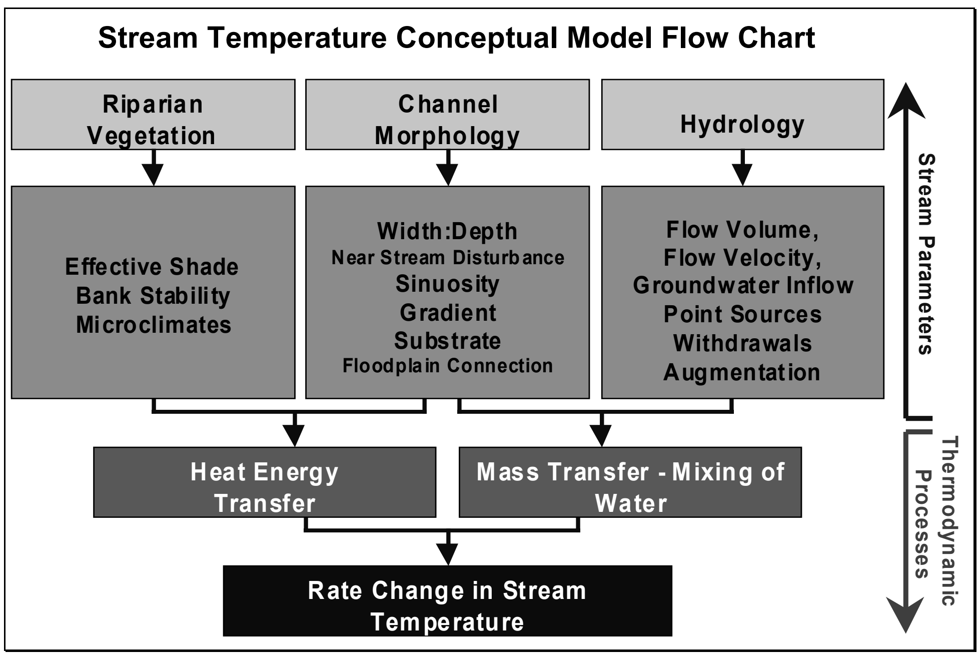

Figure I-1. Stream Temperature Conceptual Model Flow Chart

Cumulative Effects

It takes time for a water parcel to traverse the longitudinal distance of the defined reach, during which the energy processes drive stream temperature change. At any particular instant, water that enters the upstream portion of the reach is never exactly the temperature that is supported by the defined reach. As the water is transferred downstream, heat energy and hydraulic processes that are variable with time and space interact with the water parcel and induce water temperature changes. Further, heat energy is stored within this parcel of water and its temperature is the result of the heat energy processes upstream. This is commonly referred to as a cumulative temperature effect, where conditions at a site contribute to heating of an already heated parcel of stream water. The described scenario is a simplification; however, understanding the basic processes in which stream temperature changes occur over the course of a defined reach and period of time is essential.

Thermal Role of Riparian Vegetation

The role of near-stream land cover in maintaining a healthy stream condition and water quality is well documented and accepted in scientific literature (Beschta et al. 1987). Riparian vegetation plays an important role in controlling stream temperature changes. The list of significant impacts that near-stream land cover has upon the stream and the surrounding environment is long, but warrants listing.

- Near-stream vegetation produces shadows, that when cast across a stream reduce solar radiant loading. The height, width, and density of the vegetation determine the extent of this effect..
- Near-stream land cover creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity, and lower wind speeds along stream corridors.
- Near-stream vegetation affects bank stability. Specifically, channel morphology is often highly influenced by land cover type and condition, as they affect floodplain and instream roughness by contributing coarse woody debris and influencing sedimentation, stream substrate composition, and stream bank stability.

The warming of water temperature as a stream travels and drops in elevation (longitudinal heating) is a natural process. However, rates of heating can be dramatically reduced when high levels of shade exist and solar radiation loading is minimized. The overriding justification for attempting to reduce solar radiation loading is to minimize longitudinal heating. A limiting factor in reducing longitudinal stream heating is that there is a natural maximum level of shade that a given stream is capable of attaining.

Stream Surface Shade - Defined

Stream surface shade is an important parameter that controls the stream heating derived from solar radiation. Solar radiation has the potential to be the largest heat transfer mechanism in a stream system. Human activities can degrade near-stream land cover and/or channel morphology, and in turn, decrease shade. It follows that human-caused reductions in stream surface shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade levels can also serve as indicators of near-stream land cover and channel morphology condition. For these reasons, stream shade is a focus of this analytical effort.

Shade is the amount of solar energy that is obscured or reflected by vegetation or topography above a stream. Shade is expressed in units of energy per unit area per unit time or as a percent of total possible energy. Canopy cover is the percent of the sky covered by vegetation or topography. Shade producing features will cast shadows on the water, while canopy cover may not. In order to assess the ability of riparian land cover to shield a stream from solar radiation, two basic characteristics of shade must be addressed: *shade duration* and *shade quality*. The length of time that a stream receives shade is referred to as *shade duration*. The density of shade that affects the amount of radiation blocked by the shade-producing features is referred to as *shade quality*. Effective shade (Figure I-2) is amount of potential solar radiation not reaching the stream surface and is a function of *shade duration* and *shade quality*.

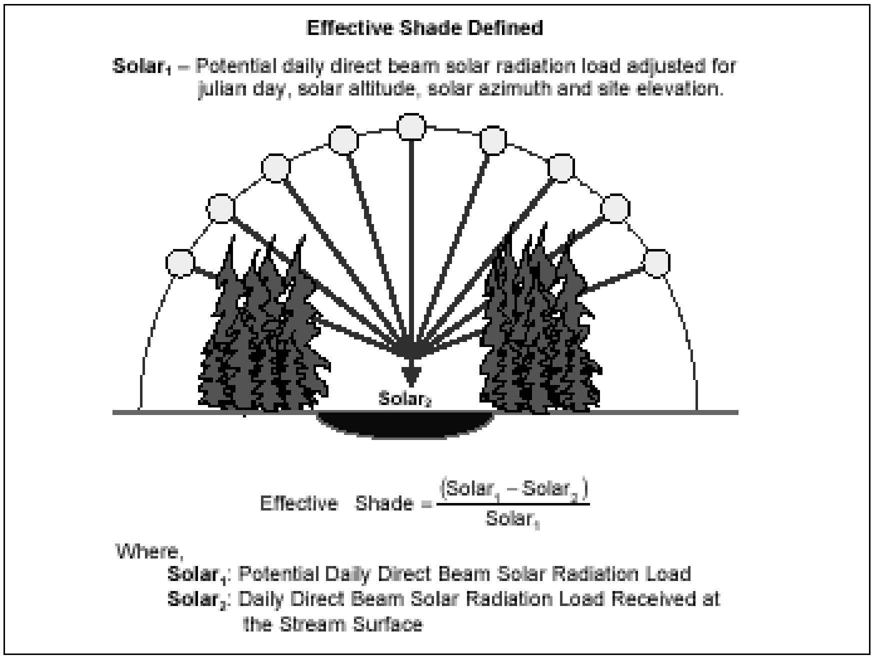

Figure I-2. Definition of Effective Shade

In the northern hemisphere, the earth tilts on its axis toward the sun during summertime months, allowing longer day length and higher solar altitude, both of which are functions of solar declination (a measure of the earth's tilt toward the sun) (Figure I-3). Geographic position (latitude and longitude) fixes the stream to a position on the globe, while aspect provides the stream/riparian orientation. Near-stream land cover height, width, and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation (i.e., produce shade) (Table I-1). The solar position has a vertical component (solar altitude) and a horizontal component (solar azimuth) that are both functions of time/date (solar declination) and the earth's rotation (hour angle measured as 15^o per hour). While the interaction of these shade variables may seem complex, the mathematics that describes them is relatively straightforward geometry. Using solar tables or mathematical simulations, the potential daily solar load can be quantified. The measured solar load at the stream surface can easily be measured with a Solar Pathfinder© or estimated using mathematical shade simulation computer programs (Boyd 1996, Park 1993).

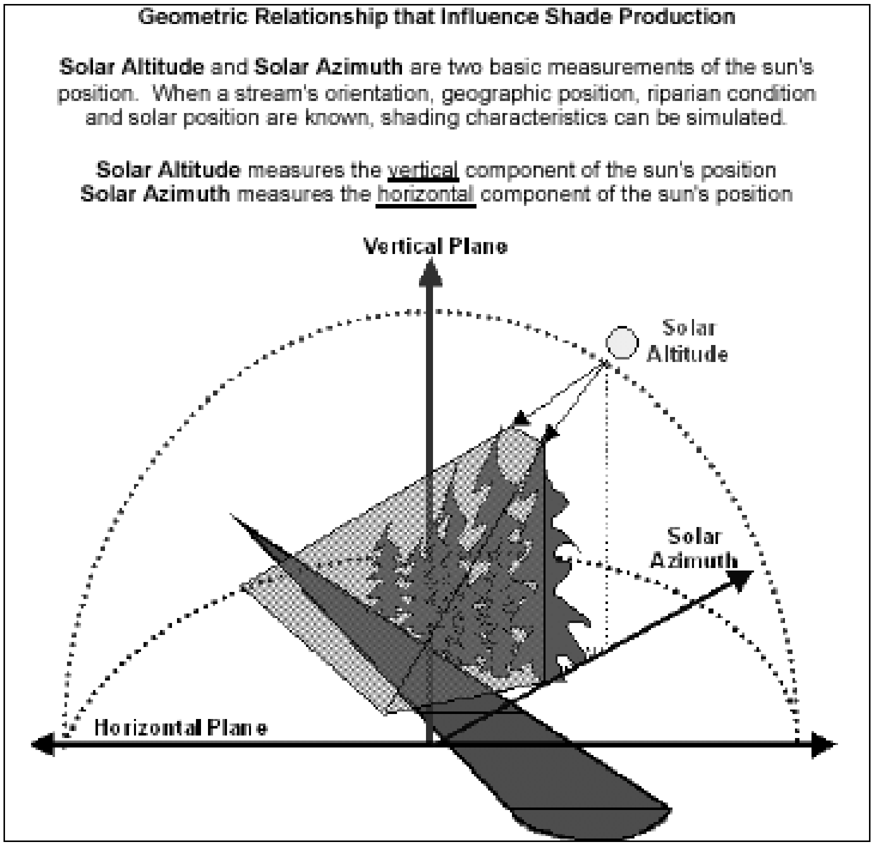

Figure I-3. Parameters that Affect Shade and Geometric Relationships

Table I-1. Factors that influence stream shade.

Description	Parameter
Season/Time	Date/Time
Stream Characteristics	Aspect, **Channel Width**
Geographic Position	Latitude, Longitude
Vegetative Characteristics	**Near-Stream Land Cover Height, Width, and Density**
Solar Position	Solar Altitude, Solar Azimuth

Bold type - influenced by human activities

Microclimate - Surrounding Thermal Environment

A secondary consequence of near-stream vegetation is its affect on the riparian microclimate. Riparian corridors often produce microclimates that surround the stream where cooler air temperatures, higher relative humidity, and lower wind speeds are characteristic. Riparian microclimates tend to moderate daily air temperatures. Relative humidity increases result from the evapotranspiration that is occurring by riparian plant communities. Wind speed is reduced simply by the physical blockage produced by riparian vegetation. Dong et al. (1998) analyzed microclimate data along 20 small streams in western Washington and found that riparian vegetation removal via timber harvests increased near stream air temperatures by up to 8 °F. Chen et al. (1995) detected that edge effects (i.e., atmospheric conditions outside of the near-stream buffer) penetrated to distances greater than 600 feet into a well-vegetated area. Riparian buffers commonly occur on both side of the stream, compounding the edge influence of the microclimate.

Brosofske et al. (1997) reported that a minimum stream buffer width of 150 feet was required to maintain soil temperatures that reflect those of a normal microclimate. Ground temperatures can be a source of heat energy to the stream. When the ground is warmer than the stream, heat will transfer from the stream bank to the water column. In fact, ground surfaces can conduct heat to a stream hundreds of times faster than an air column surrounding the stream. Solids (ground surfaces) have conductivities on the order of 500 to 3,500 times greater than gases (air) (Halliday and Resnick 1988). Impoverished riparian areas that allow excessive stream bank warming will introduce heat into the stream faster than cooler, highly vegetated stream banks. Riparian condition is again implicated as a controlling factor in stream temperature dynamics, in part because ground/soil temperatures are a function of shading.

Air affects stream temperatures at a slower *rate* than the ground. Nevertheless, this should not be interpreted to mean that air temperatures do not affect stream temperature. Air can deliver heat to a stream via the convection/conduction pathway, which is the slowest of the water energy transfer processes (Bowen 1926, Beschta and Weatherred 1984, Boyd 1996, Chen 1996). However, prolonged exposure to air temperatures warmer than the stream can induce gradual stream heating. Thus, a cooler microclimate will induce less stream warming.

Thermal Role of Channel Morphology

Changes in channel morphology, mainly channel widening, impact stream temperatures. As a stream widens, the surface area exposed to radiant sources and the ambient air temperature increases, resulting in increased energy exchange between the stream and its environment (Boyd 1996). Further, wide channels are likely to have relatively little shade due to the distance between the banks and the increased surface area to shade ratio. Conversely, narrow channels are more likely to receive a lot of shade. An additional benefit inherent of narrow/deep channels is the higher frequency of pools that contribute to aquatic habitat.

Channel widening is often related to degraded riparian conditions that allow increased stream bank erosion and sedimentation of the streambed, both of which correlate strongly with riparian vegetation type and condition (Rosgen 1994). Riparian vegetation strengthens the stream bank with its roots (rooting strength) and contributes to floodplain and stream bank roughness that dissipates erosive energies associated with flowing water. Established or mature woody riparian vegetation provide the highest level of rooting strength and floodplain and stream bank roughness. Annual (grassy) riparian vegetation communities offer less rooting strength and floodplain and stream bank roughness.

Channel morphology is not solely dependent on riparian conditions. Sedimentation can deposit material in the channel, fill pools, and agrade the streambed, reducing channel depth and increasing channel width. High flow events play a major role in shaping the stream channel. Channel modification usually occurs during high flow events. Naturally, land uses that affect the magnitude and timing of high flow events may negatively impact channel width and depth. Riparian vegetation conditions will affect the resilience of the stream banks and floodplain during periods of sediment introduction and high flow. Disturbance processes may have drastically differing results depending on the ability of riparian vegetation to shape and protect channels. Riparian vegetation composition and condition affect channel morphology by:

- **Building stream banks:** Vegetation traps suspended sediments, encourages deposition of sediment in the floodplain, and reduces incoming sources of sediment.
- **Maintaining stable stream banks:** High rooting strength and high stream bank and floodplain roughness prevent stream bank erosion.
- **Reducing flow velocity (erosive kinetic energy):** Vegetation supplies large woody debris to the active channel, creates high pool:riffle ratios, and adds channel complexity that reduces shear stress exposure to stream bank soil particles.

Thermal Role of Hydrology

Brown (1969) proposed that water temperature change is a proportional function of heat exchange per unit volume:

$$\Delta T_w \propto \frac{\Delta Heat \quad Energy}{Volume}$$

Therefore, large volume streams are less responsive to temperature change than are low flow streams. Specifically, stream flow volume will affect the wetted channel dimensions (width and depth), flow velocity, travel time, and the stream assimilative capacity. Human-related reductions in flow volume can have a significant influence on stream temperature dynamics, most likely increasing diurnal variability in stream temperature. Figure I-4 illustrates the estimated mean August flow conditions for hydrological subunits within the South Fork Clearwater River subbasin (Lipscomb 1998). As can be seen in this image, stream flow conditions are very low throughout the subbasin during the summer, especially within the subbasin tributaries.

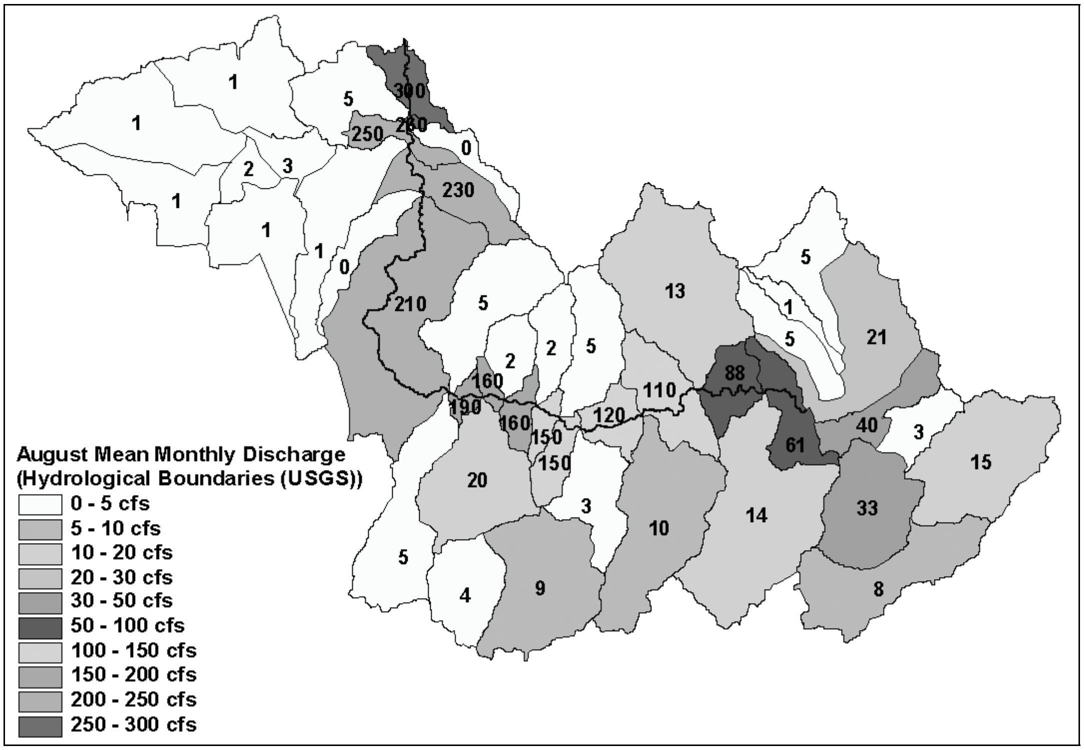

Figure I-4. **Estimated August Mean Monthly Flow Conditions for the South Fork Clearwater River Subbasin (Lipscomb 1998)**

Thermal Role of Ground Water

Ground water inflow has a cooling effect on summertime stream temperatures. Subsurface water is insulated from surface heating processes. Ground water temperatures fluctuate little and are cool (45 ^oF to 55 ^oF). Many land use activities that disturb riparian vegetation and associated floodplain areas may affect the surface water connectivity to ground water sources. Ground water inflow not only cools summertime stream temperatures, but also augments summertime flows. Reductions in or elimination of ground water inflow will have a compounding warming effect. The ability of riparian soils to capture, store and slowly release ground water is largely a function of floodplain/riparian area health.

The effects of ground water hydrology were not analyzed in this total maximum daily load (TMDL) effort. However, targets developed as part of this TMDL should passively promote the protection and creation of ground water areas and the connectivity of these areas with the stream.

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